Charm CPV and rare decays at LHCb

Michael J. Morello
michael.morello@sns.it
Scuola Normale Superiore and INFN, Pisa (Italy)

on behalf of the LHCb Collaboration

SCUOLA NORMALE SUPERIORE

INFN

LHCb

The role of charm physics

- Charm is the only up-type quark allowing full range of probes for mixing and CP Violation:
  - top quarks do not hadronize → no T^0 - $\overline{T}^0$ oscillations
  - no π^0-π^0 oscillations possible (particle and anti-particle are identical)

- CPV predicted to be small within SM, since mixing and relevant amplitudes are described, to an excellent approximation, by the physics of the first two generations only.
  - from CKM CPV ~ $O(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim 10^{-3}$ or less
  - huge effort from theoreticians to keep under control QCD effects.

- Charm transitions are a unique portal (complementarity wrt B and K mesons) for obtaining a novel access to flavor dynamics with the experimental situation being a priori favorable ("low SM background").

- Unprecedented huge samples of D decays are necessary (much larger of 10^6 events needed) in order to approach SM predictions.

Charm Physics at LHCb: a new era

- All c species produced in pp collisions. In the acceptance p_T<8GeV/c and 2.0<y<4.5:

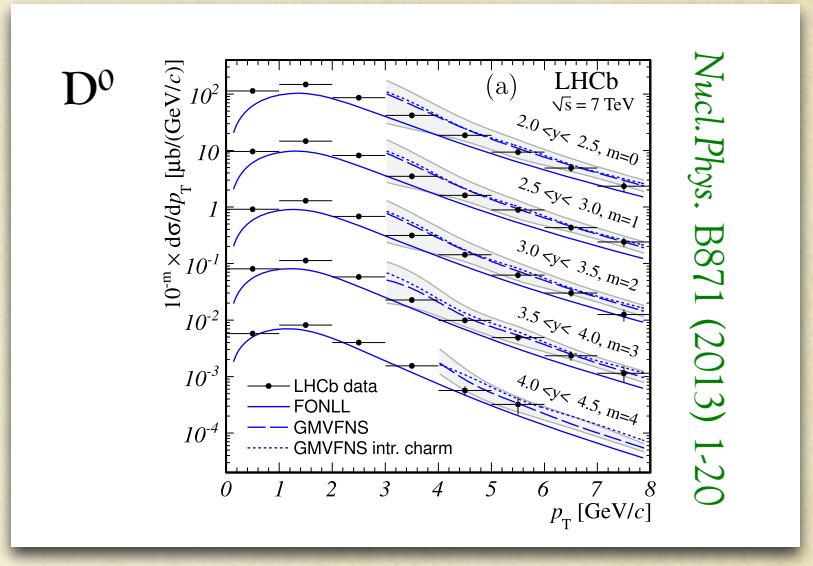
	Cross-section (μb)
D^0	$1661 \pm 16 \pm 128 \pm 2$
D^+	$645 \pm 11 \pm 72 \pm 8$
D^{*+}	$677 \pm 26 \pm 77 \pm 19$
D_s^+	$197 \pm 14 \pm 26 \pm 8$
Λ_c^+	$233 \pm 26 \pm 71 \pm 14$

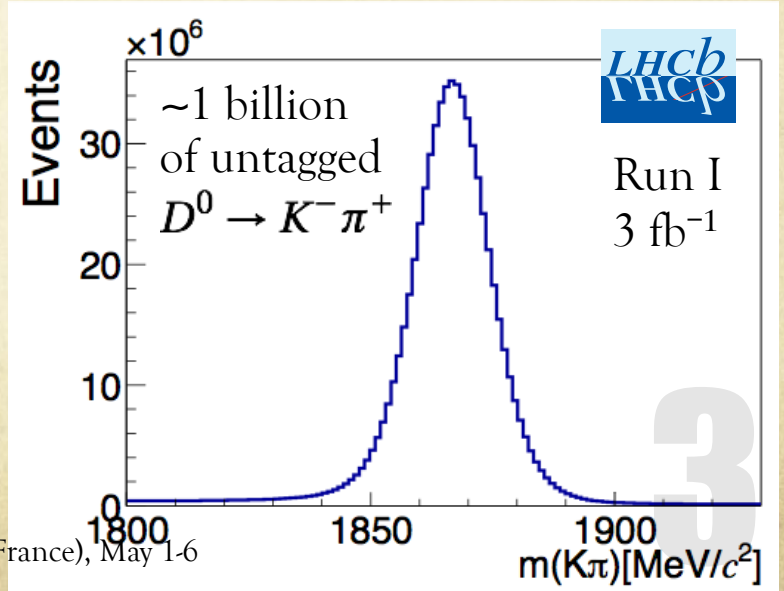
- Produced ~5×10^{12} D^0 and ~2×10^{12} D^{*+} mesons in $3\,fb^{-1}$ of data at $L_{inst} = 4\times10^{32}\,cm^{-2}s^{-1}$.

- ... and reconstructed for physics in RunI
  - ~1×10^9 $D^0 \to K^-\pi^+$,
  - ~0.1×10^9 $D^0 \to K^-\pi^+$ from $D^{*+} \to D^0\,\pi^+$

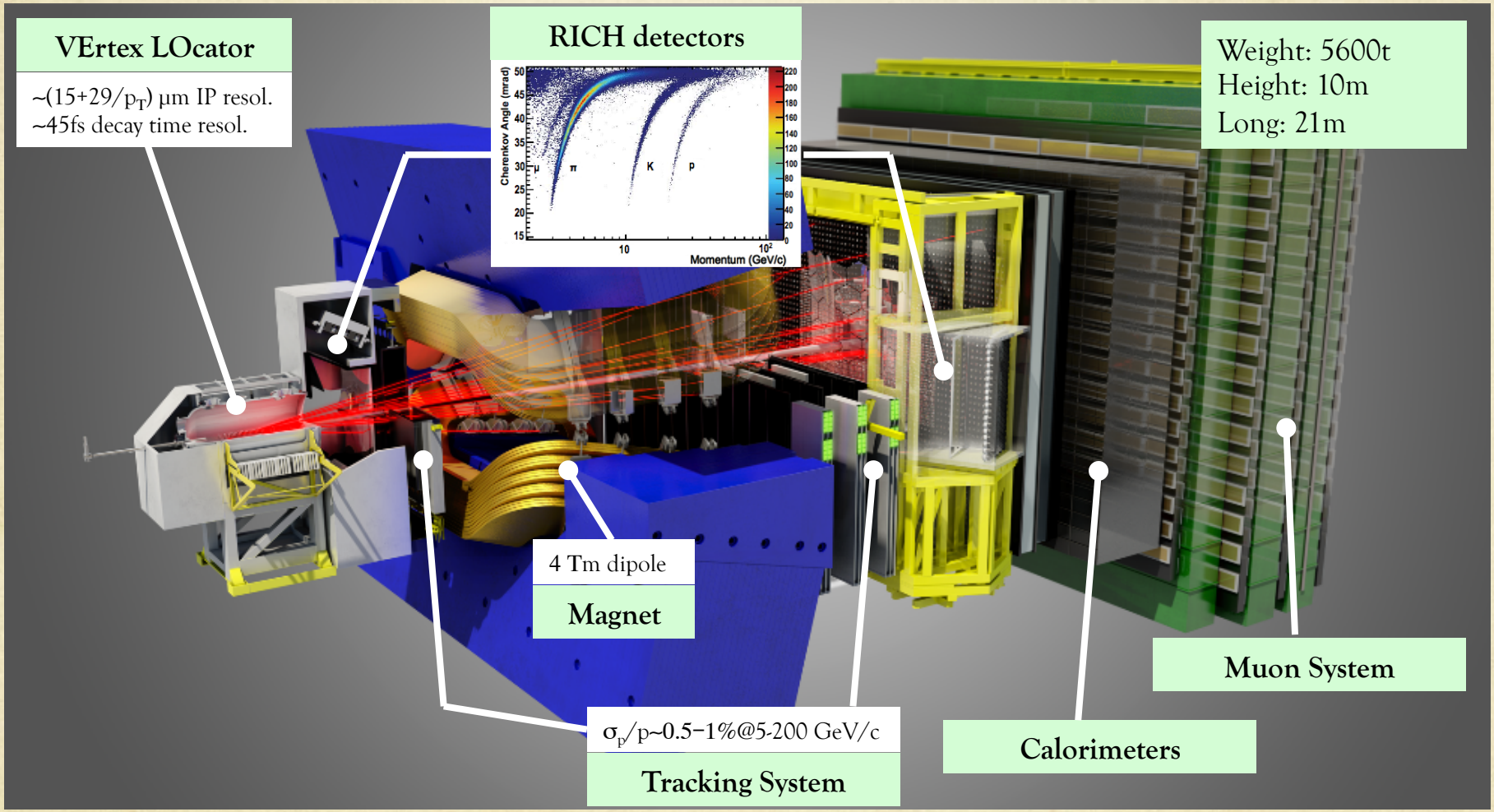
- **About a factor 20-30 lager than samples collected by the CDF experiment in 10 fb^{-1}.**

- **Just the beginning of new era aiming at the full exploitation of the Large Hadron Collider.**





The LHCb detector



The LHC detector at LHC, JINST 3 (2008) S08005

Excellent trigger capabilities (Level-0 of custom electronics + HLT of commercial CPUs) to handle 11MHz of visible physics collisions. Events written on tape extremely fast at 2.5KHz, where typical event size is 60-100KBytes in RunI. See talk from B. Sciascia on "Trigger performances in RunII".

$\Delta A_{CP}(D^0 \to h^+h^-)$

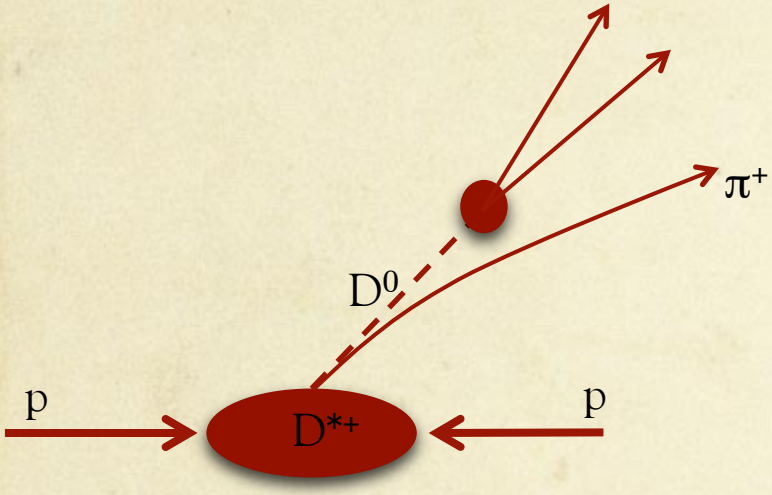
- Effects of "direct" CP violation can be isolated by taking the difference between the time-integrated CP asymmetries in the K^+K^- and $\pi^+\pi^-$ modes:

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \\ &\approx \Delta a_{CP}^{\rm dir}\left(1 + \frac{\overline{\langle t \rangle}}{\tau}\, y_{CP}\right) + \frac{\Delta\langle t \rangle}{\tau}\, a_{CP}^{\rm ind}, \end{aligned}$$

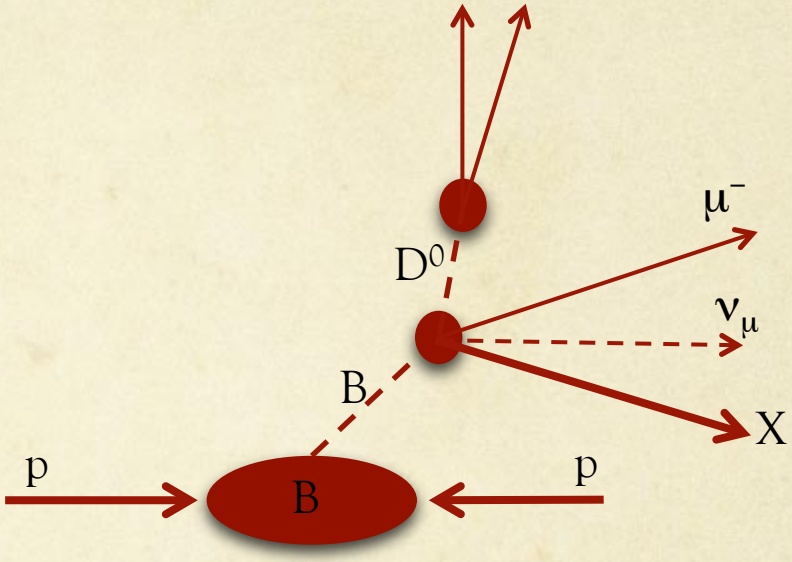
- where a residual experiment-dependent contribution from indirect CP violation can be present, due to the fact that there may be a decay time dependent acceptance function that can be different for the K^+K^- and $\pi^+\pi^-$ channels.

- Well suited for LHCb because of cancellation of instrumental and production asymmetries. (See P. Marino's poster for more details.)

D^0 flavour tagging



$D^{*+} \rightarrow D^0 \pi^+$ decay chain
from charge of soft pion



semi-leptonic $B \rightarrow D^0 \mu^- \nu_\mu X$
from charge of muon

Raw asymmetries (soft pion tag)

$$A_{\text{raw}}(f) = \frac{N[D^{*+} \to D^0(f)\pi_s^+] - N[D^{*-} \to \bar{D}^0(f)\pi_s^-]}{N[D^{*+} \to D^0(f)\pi_s^+] + N[D^{*-} \to \bar{D}^0(f)\pi_s^-]}$$

Physics observable

~1%

$$A_{\text{raw}}(f) \approx A_{CP}(f) + A_{\text{D}}(f) + A_{\text{D}}(\pi_s^+) + A_{\text{P}}(D^{*+})$$

detection asymmetries in reconstructing the final **Null for CP-eigenstates f=ππ,KK.**

detection asymmetries in reconstructing the soft pion**. It cancels out in the difference.**

D^{*+} production asymmetry, mainly arising from the hadronisation of charm quark in pp collisions. **It cancels out in the difference.**

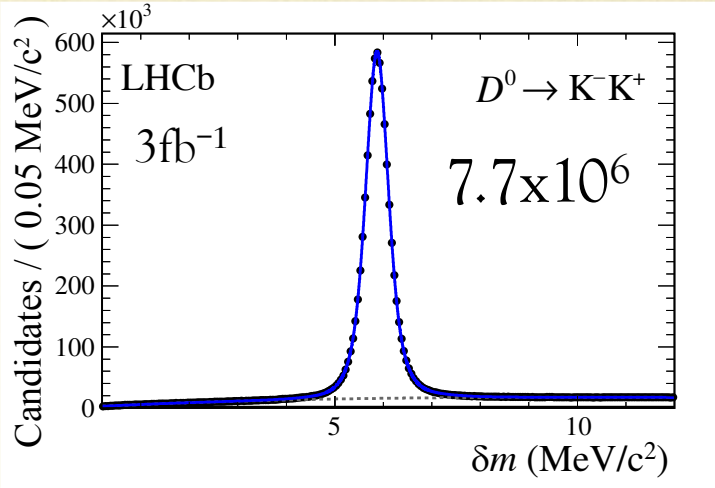
$$\Delta A_{CP} = A_{\text{raw}}(K^-K^+) - A_{\text{raw}}(\pi^-\pi^+) = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

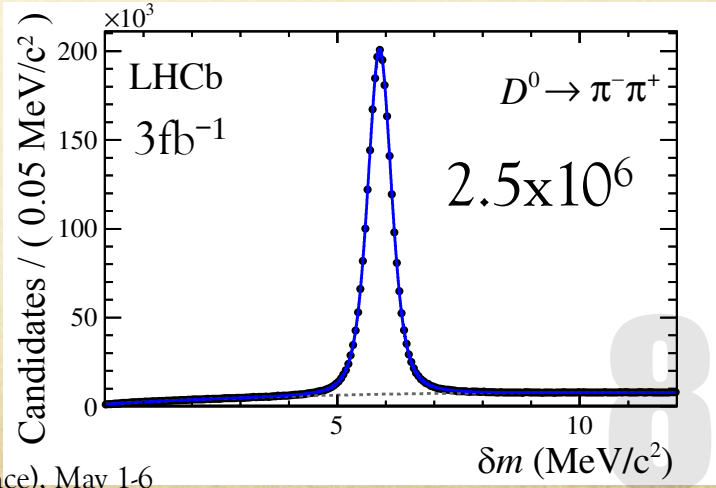
To account for an imperfect cancellation of detection and production asymmetries due to the difference in the kinematic properties, distributions of D* decays of KK reweighted to those of ππ.

Analysis in a nutshell

LHCb-PAPER-2015-055
arXiv:1602.03160, Accepted by PRL

- Selection:
  - Rectangular cuts on momenta, lifetime and quality of decays products.
  - Removal of kinematics regions of soft pion with large (up to 100%) instrumental raw asymmetries.
  - Tight cuts on K and π PID variables to suppress mis-ID backgrounds.
  - Cut on D^0 mass to suppress multi-body decays.
  - Cut on D^0 IPχ^2 (vertex compatibility) to suppress backgrounds from secondary decays.
- Simultaneous fit of $\delta m = m(D^{*+}) - m(D^0) - m_\pi$ distributions for D^{*+} and D^{*-} data samples.
- Extensive checks of result stability as a function of many variables: magnet polarity, beam energy, trigger categories, kinematic variables, PID requirements, etc...





$\Delta A_{CP}(D^0 \to h^+h^-)$: result in $3fb^{-1}$

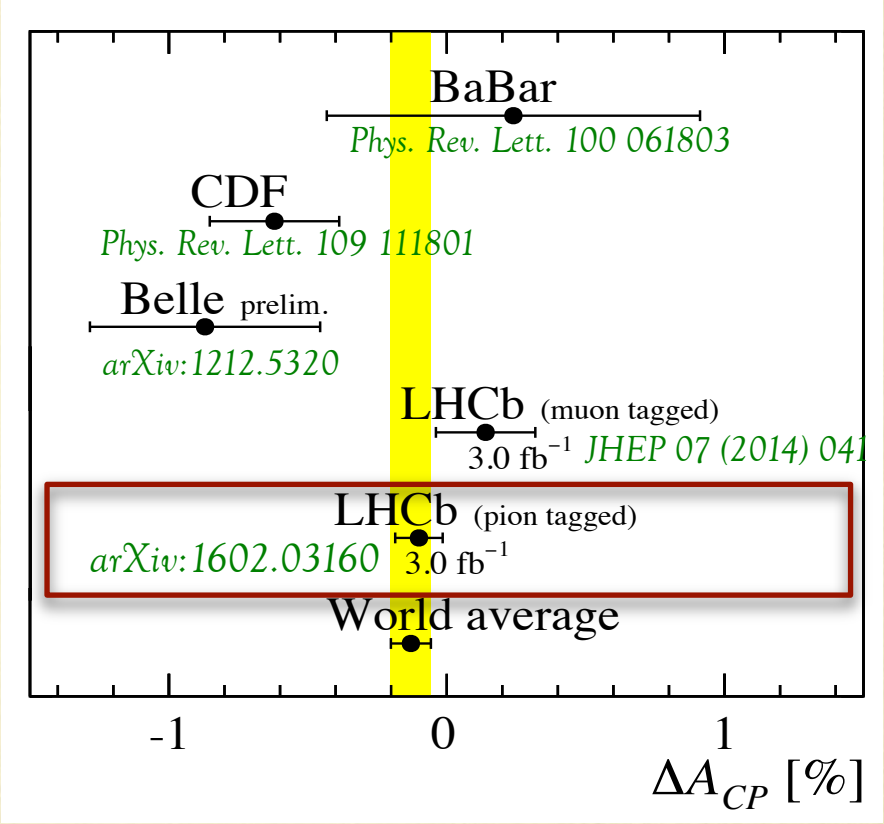
$$\Delta A_{CP} = (-0.10 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst}))\ \%$$

LHCb-PAPER-2015-055, arXiv:1602.03160, Accepted by PRL for publication.

- Final LHCb words with full Run I data.
  - Compatible with null hypothesis with a statistical precision below 10^{-3} (LHCb Run II is currently ongoing).
  - Systematic uncertainty already approaching 10^{-4} level.
- Fully compatible with the independent LHCb muon-tagged result [*JHEP 07 (2014) 041*]: $\Delta A_{CP} = (+0.14 \pm 0.16\,(\text{stat}) \pm 0.08\,(\text{syst}))\%$.
- Along with the LHCb A_Γ measurement, the most precise measurements of CP Violation in the charm and beauty sector.

ΔA_{CP} state-of-the-art

- This supersedes previous published LHCb result on 0.6 fb^{-1}
  $\Delta A_{CP} = (-0.82 \pm 0.21)\%$
  [*PRL 108(2012), 111602*].
- and preliminary result on 1fb^{-1}
  $\Delta A_{CP} = (-0.34 \pm 0.18)\%$
  [*LHCb-CONF-2013-003*].
- Factors contributing to the change
  - larger data sample size
  - improved detector calibration and reconstruction software.



Naïve weighted average (neglecting indirect CPV contribution) gives $\Delta A_{CP} = (-0.129 \pm 0.072)\%$ fully dominated by LHCb results.

LHCb CPV searches in $D^0 \to h^+h^-$

Using only experimental LHCb inputs for A_Γ, y_{CP}

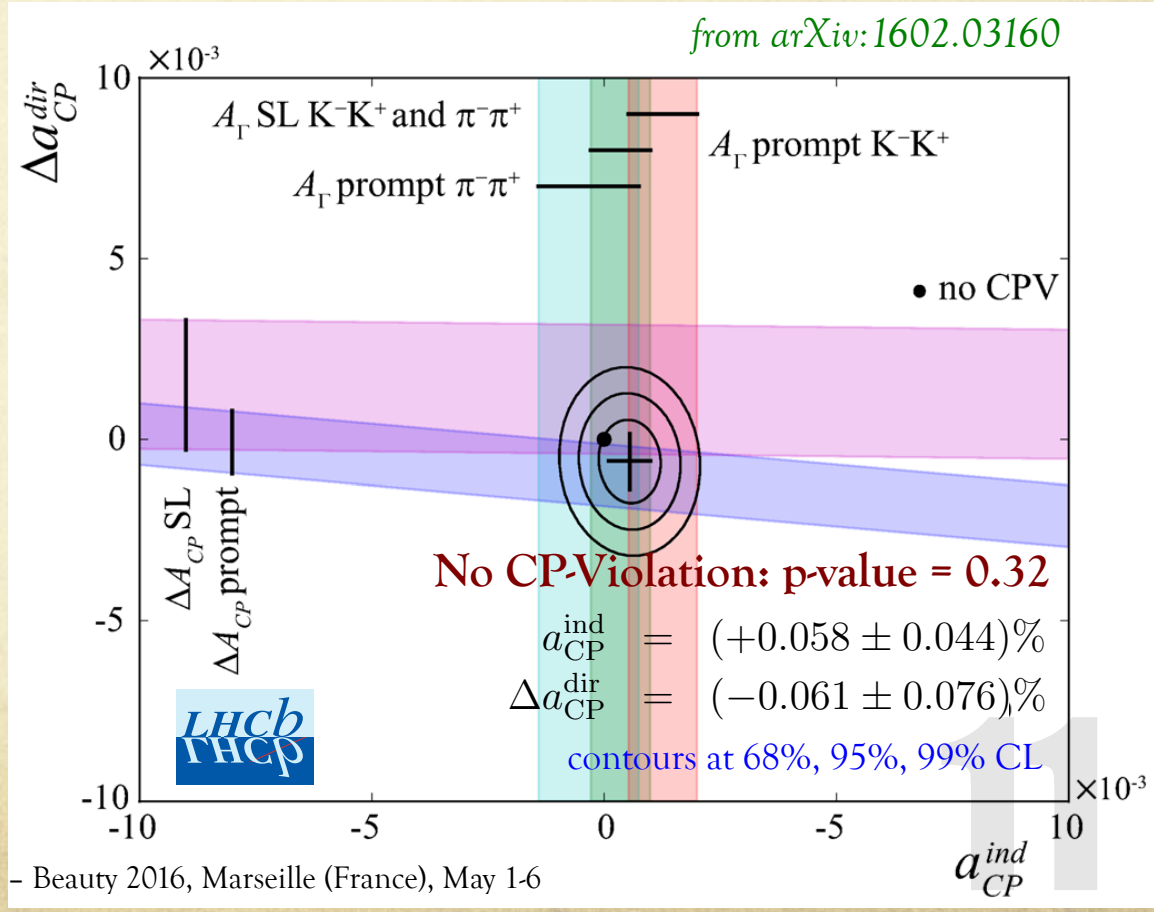
$$\Delta A_{CP} \approx \Delta a_{CP}^{\rm dir}\left(1+\frac{\overline{\langle t\rangle}}{\tau}y_{CP}\right)+\frac{\Delta\langle t\rangle}{\tau}a_{CP}^{\rm ind}$$

HFAG (Winter-2016) averages including results from all experiments:

$$a_{\rm CP}^{\rm ind} = (+0.056 \pm 0.040)\%$$
$$\Delta a_{\rm CP}^{\rm dir} = (-0.137 \pm 0.070)\%$$

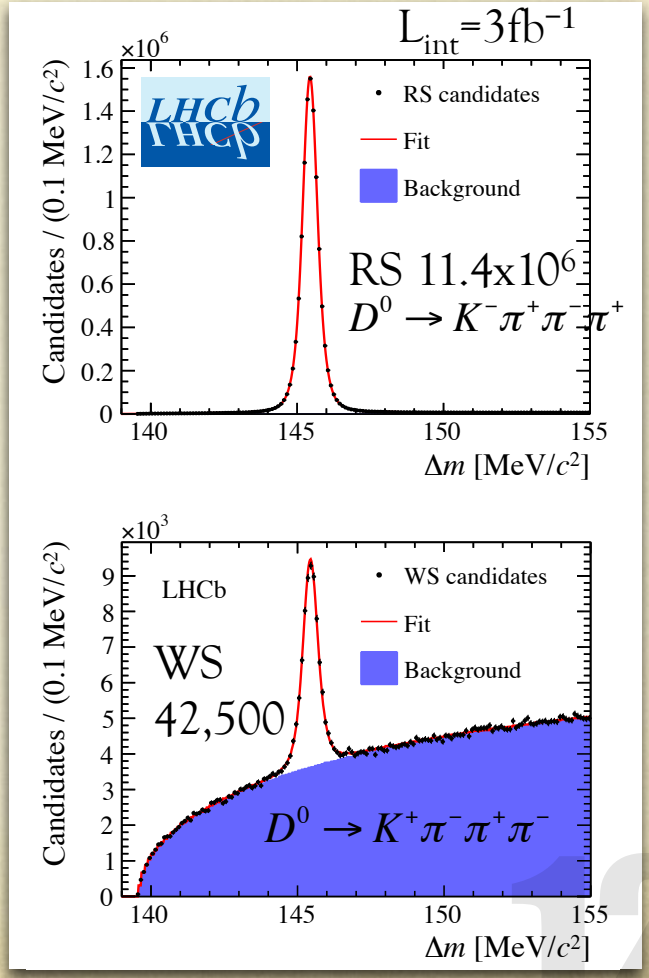
compatible with no-CPV at 6.5% CL.

Average fully dominated by LHCb measurements.



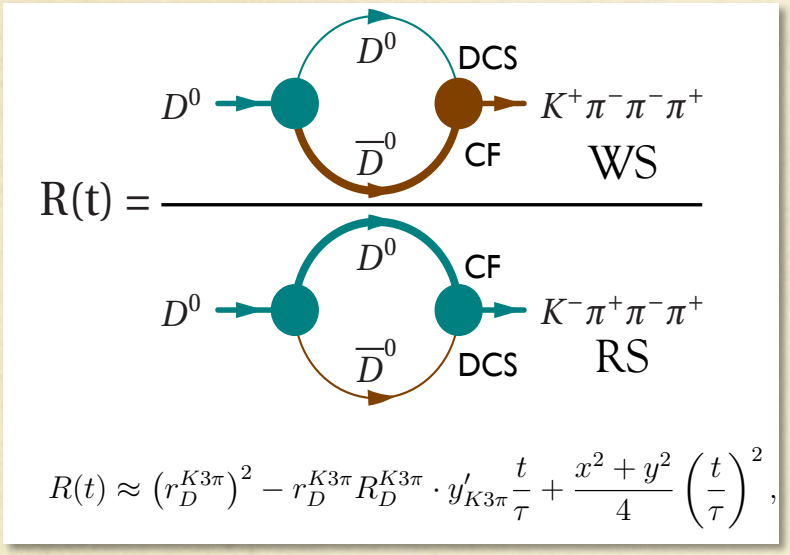
Observation of D^0 mixing in multi-body decay

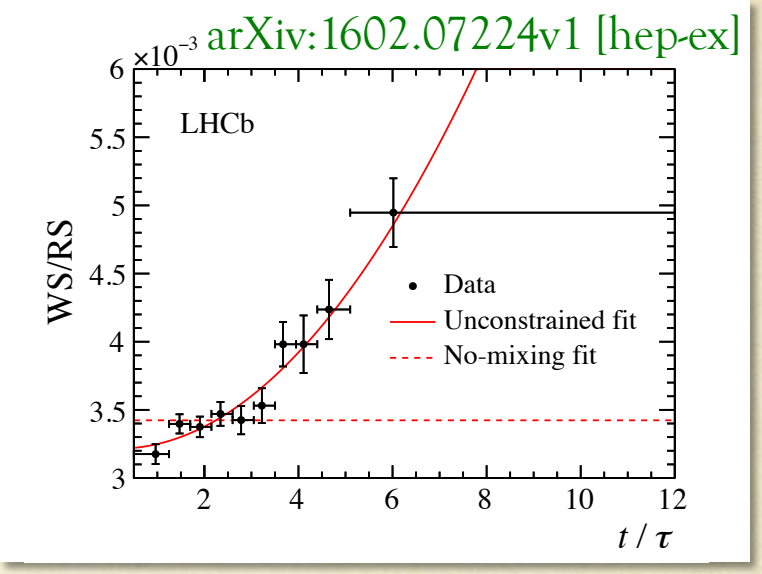
- Fully inspired to the the two-body decays analysis [*PRL 110 (2013),101802*]
  - D^0 flavour tagged with $D^{*+} \to D^0 \pi^+$ decay,
  - Time dependence of WS/RS(t) ratio.
- Analysis challenges:
  - "higher" combinatorial and mis-reconstructed background,
  - contribution of secondary B-decays,
  - trigger efficiency depends on its location in the 5-dim phase space of the decay.



arXiv:1602.07224v1 [hep-ex], submitted to PRL.

Observation of D^0 mixing in multi-body decay





No mixing hypothesis rejected at 8.2σ.
First time for a multi-body decays.

Uncertainty on $R_D y'$ reduces by 9% when systematics on WS/RS ratio is set to zero.

Constraint on $R_D^{K3\pi} y'_D{}^{K3\pi}$ is an essential ingredient for γ mesurement in $B^+ \rightarrow D^0 K^+ \rightarrow [K^-\pi^+\pi^-\pi^+]K^+$.

Fit Type χ^2/ndf (p-value)	Parameter	Fit result
Unconstrained 7.8/7 (0.35) →	$r_D^{K3\pi}$	$(5.67 \pm 0.12) \times 10^{-2}$
	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$(0.3 \pm 1.8) \times 10^{-3}$
	$\frac{1}{4}(x^2+y^2)$	$(4.8 \pm 1.8) \times 10^{-5}$
Mixing-constrained 11.2/8 (0.19) →	$r_D^{K3\pi}$	$(5.50 \pm 0.07) \times 10^{-2}$
	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$(-3.0 \pm 0.7) \times 10^{-3}$
	x	$(4.1 \pm 1.7) \times 10^{-3}$
	y	$(6.7 \pm 0.8) \times 10^{-3}$

Rare charm decays

- Flavor Changing Neutral Currents (FCNCs) are processes that change the flavor of a fermion current without altering its charge.
  - may occur in the SM beyond the tree level, but they are highly suppressed (GIM mec.),
  - NP could significantly enhance FCNC.
- Lepton flavour violating are forbidden within the SM
  - probe potential contributions from new processes and particle at mass scales beyond the reach of the direct searches.

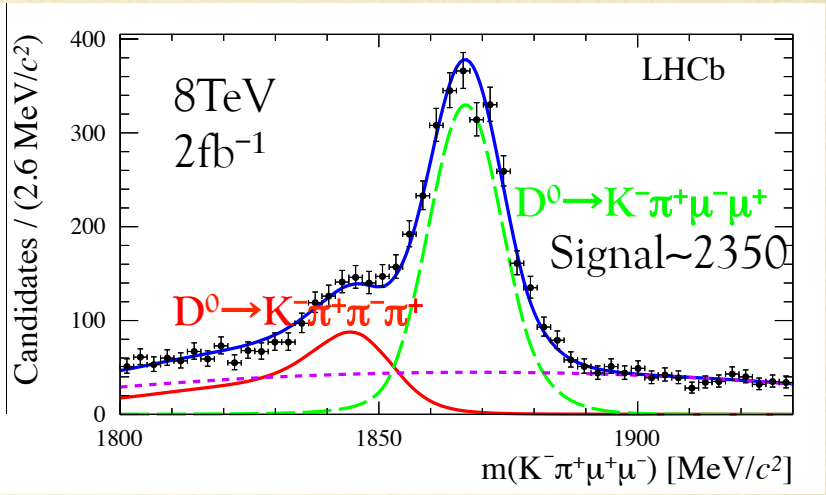
First observation of $D^0 \to K^- \pi^+ \mu^- \mu^+$ [*arXiv:1510.08367, submitted to PLB*]
Search for the decay $D^0 \to \pi^- \pi^+ \mu^- \mu^+$ [*PLB 728 (2014) 234*]
Search for $D^0 \to \mu^+ \mu^-$ [*Phys. Lett. B 725,15 (2013)*]
Search for $D^+_{(s)} \to \pi^+ \mu^+ \mu^-$ [*PLB 724 (2013) 203*]

Search of $D^0 \to e^{\pm} \mu^{\mp}$ [*PLB 754 (2016) 167*]

First observation of $D^0 \to K^-\pi^+\mu^-\mu^+$

- Short-distance contribution of the inclusive $D \to X\mu^+\mu^-$ ~O(10^{-9}) [*PRD83,(2011)114006*]
- However with "long-distance" contribution trough tree diagrams involving vector resonances such as $X=\phi,\rho^0,\omega$ BR~O(10^{-6}) [*PRD83,(2011)114006,PRD76(2007), 074010;JHEP 04(2013)135*]
- In the region 675 <m($\mu^+\mu^-$)< 875 MeV/c^2.
- $D^0 \to K^-\pi^+\pi^-\pi^+$ as normalization. BR from CLEO experiment [*PRD89(2014),072002*]

arXiv:1510.08367, submitted to PLB



arXiv:1510.08367, submitted to PLB

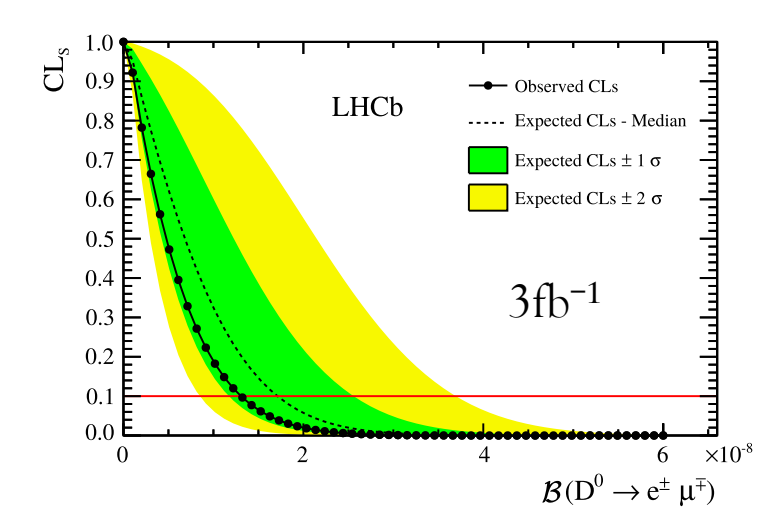
$$\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12\,(\text{stat}) \pm 0.40\,(\text{syst})) \times 10^{-6}.$$

Lower than one order of magnitude of previous most stringent upper limit from B-Factories. Compatible with SM expectation of 6.7x10^{-6} [*JHEP 04(2013)135*] in the full dimuon mass range.

Search for LFV $D^0 \to e\mu$

- Forbidden in the SM.
  - however it is predicted to occur in several SM extensions, with rates varying by up to eight order of magnitudes [$10^{-6} - 10^{-14}$].
- Most stringent limit from Belle BR<2.6×10^{-6} at 90%CL.
- $D^0 \to K^-\pi^+$ as normalization

PLB 754 (2016) 167



PLB 754 (2016) 167

$$\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 1.3 \times 10^{-8} \text{ at 90\% CL}$$

Conclusions

- LHC is a super-duper charm-factory, and LHCb is doing an excellent job collecting the largest ever data samples.
- In Run I (especially for two-body golden modes) :
  - Achieved statistical precision below 10^{-3}, and systematics already close to the impressive value of 10^{-4}.
  - No hints of CP-violation (or anomalies) have been found so far, however LHCb has just started to approach SM expectations.
  - Limits on rare decays improved by orders of magnitude.
- LHCb Run II is currently ongoing with an "improved" trigger system and the size of our data samples are expected to increase much more than proportionally to the integrated luminosity.

Conclusions (cont'd)

- Probing today the charm sector at unprecedented level of precision (up to and beyond 10^{-4}) is extremely important not only by itselfs, but also because
- it provides us the concrete feeling that systematic walls are still far and "very precise" beauty (and charm) physics can be done at future HL-LHC experiments. Please take a look at
  - G. Simi's talk: LHCb-Upgrade
  - F. Teubert's talk: Beyond LHCb upgrade: long term plans.

Thanks

Backup

And many many other measurements...

TITLE	DOCUMENT NUMBER	JOURNAL	SUBMITTED ON
First observation of $D^0 - \bar{D}^0$ oscillations in $D^0 \to K^+\pi^-\pi^+\pi^-$ decays and measurement of the associated coherence parameters	PAPER-2015-057	PRL	23 Feb 2016
Measurement of the difference of time-integrated CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays	PAPER-2015-055	PRL	09 Feb 2016
Study of $D_{sJ}^{(*)+}$ mesons decaying to $D^{*+}K_S^0$ and $D^{*0}K^+$ final states	PAPER-2015-052	JHEP 02 (2016) 133	07 Jan 2016
Search for the lepton-flavour violating decay $D^0 \to e^\pm\mu^\mp$	PAPER-2015-048	Phys. Lett. B754 (2016) 167	01 Dec 2015
First observation of the decay $D^0 \to K^-\pi^+\mu^+\mu^-$ in the ρ^0-ω region of the dimuon mass spectrum	PAPER-2015-043	PLB	28 Oct 2015
Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s}$ = 13 TeV	PAPER-2015-041	JHEP 03 (2016) 159	06 Oct 2015
Model-independent measurement of mixing parameters in $D^0 \to K_S^0\pi^+\pi^-$ decays	PAPER-2015-042	JHEP 04 (2016) 033	06 Oct 2015
Studies of the resonance structure in $D^0 \to K_S^0K^\pm\pi^\mp$ decays	PAPER-2015-026	Phys. Rev. D93 (2016) 052018	22 Sep 2015
Measurement of the time-integrated CP asymmetry in $D^0 \to K_S^0K_S^0$ decays	PAPER-2015-030	JHEP 10 (2015) 055	25 Aug 2015
Measurement of indirect CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays	PAPER-2014-069	JHEP 04 (2015) 043	27 Jan 2015
Search for CP violation in $D^0 \to \pi^-\pi^+\pi^0$ decays with the energy test	PAPER-2014-054	Phys. Lett. B740 (2015) 158	15 Oct 2014
Search for CP violation using T-odd correlations in $D^0 \to K^+K^-\pi^+\pi^-$ decays	PAPER-2014-046	JHEP 10 (2014) 005	06 Aug 2014
Search for CP violation in $D^\pm \to K_S^0K^\pm$ and $D_s^\pm \to K_S^0\pi^\pm$ decays	PAPER-2014-018	JHEP 10 (2014) 025	10 Jun 2014
Measurement of CP asymmetry in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays	PAPER-2014-013	JHEP 07 (2014) 041	12 May 2014

.....

.....

http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_Charm.html

A_Γ :indirect CPV in $D^0 \to h^+h^-$

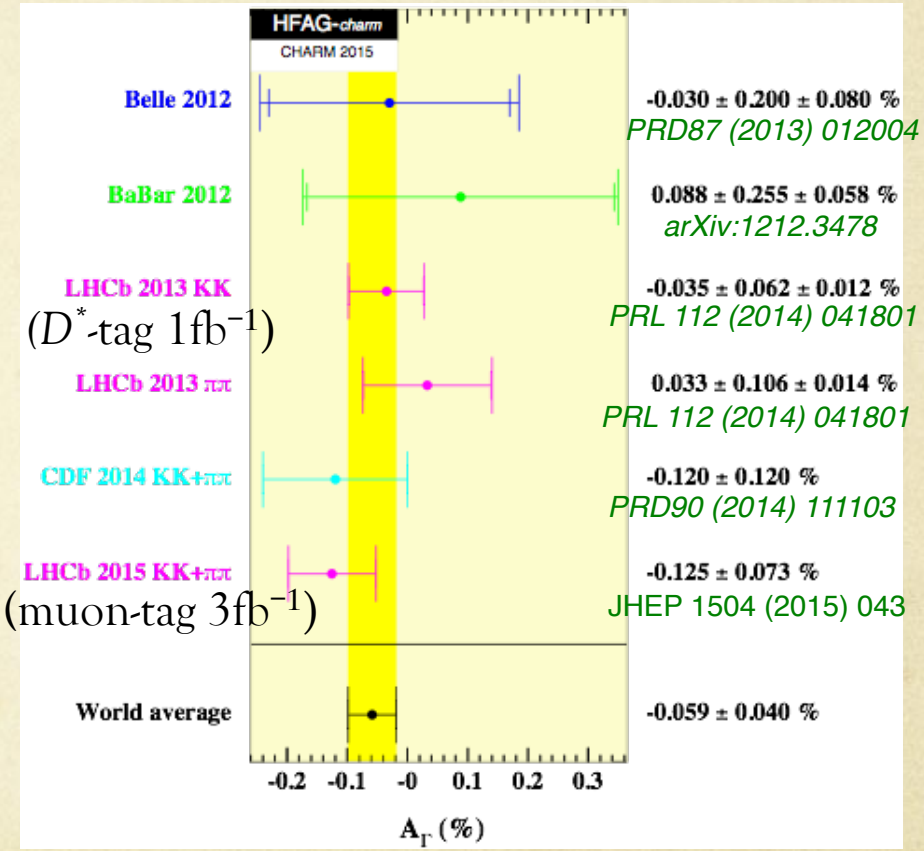
Time-dependent CP asymmetry:

$$A_{CP}(t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)} \simeq a_{CP}^{dir} - \frac{t}{\tau_{D^0}} A_\Gamma$$

A_Γ measures CPV in the mixing (A_m) and in the decay (A_d):

$$A_\Gamma \simeq \left[\frac{1}{2}(A_m + A_d)\, y \cos\phi - x \sin\phi\right]$$

$$A_m = \left|\frac{q}{p}\right|^2 - 1 \qquad A_d = \left|\frac{\overline{A}_f}{A_f}\right|^2 - 1$$



World best measurement from LHCb D^*-tagged using 1fb^{-1} of integrated luminosity. Measurement on full RunI data sample (3fb^{-1}) expected to be released soon.